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14. ABSTRACT

The program at Arizona State University (ASU) consisted of complementary experimental, computational, and flight-test elements that examined the aerodynamics of Micro Aerial Vehicles (MAVs). All these components supported the actual design of our MAV, called MAVRIC (Micro Aerial Vehicle Research Initiative and Competition) and which competed for two years against other university teams. MAVs are characterized by low operating chord Reynolds numbers and thus present challenges in viscous aerodynamics. Our studies focused on the effects on performance of different wing-body-juncture and wing-tip designs. MAV aerodynamics is strongly affected by the wing-tip vortices which extend over a significant amount of span. Blending the wing and fuselage and adding winglets provided a reduction in the extent of these vortices as well as a refocusing of them away from the lifting surface.

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AERODYNAMIC STUDIES OF MICRO AIR VEHICLES

AFOSR GRANT NUMBER F49620-99-1-0089

FINAL TECHNICAL REPORT

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Abstract. The program at Arizona State University (ASU) consisted of complementary experimental, computational, and flight-test elements that examined the aerodynamics of Micro Aerial Vehicles (MAVs). All these components supported the actual design of our MAV, called MAVRIC (Micro Aerial Vehicle Research Initiative and Competition) and which competed for two years against other university teams. MAVs are characterized by low operating chord Reynolds numbers and thus present challenges in viscous aerodynamics. Our studies focused on the effects on performance of different wing-body-juncture and wing-tip designs. MAV aerodynamics is strongly affected by the wing-tip vortices which extend over a significant amount of span. Blending the wing and fuselage and adding winglets provided a reduction in the extent of these vortices as well as a refocusing of them away from the lifting surface.

Introduction. Small autonomous aerial vehicles are being designed that are sized down to no more than 6 inches (150 mm) in any direction and operate at chord Reynolds numbers under 100,000. Because of their size and unique flight conditions, these MAVs offer new challenges to aerodynamics, controls and even basic design issues.

The development and evaluation of aerodynamic technologies for MAVs must include the effects of viscosity and three dimensionality that are inherent to their relatively low speeds and low chord Reynolds numbers. One expects local failure of classical inviscid aerodynamics in this flow regime so it may be appropriately called *viscous aerodynamics*. Moreover, the flight environment is characterized as turbulence-free but with large unsteady gusts and lulls. Any design methodology and control schemes to be used on MAVs must be designed with these effects in mind.

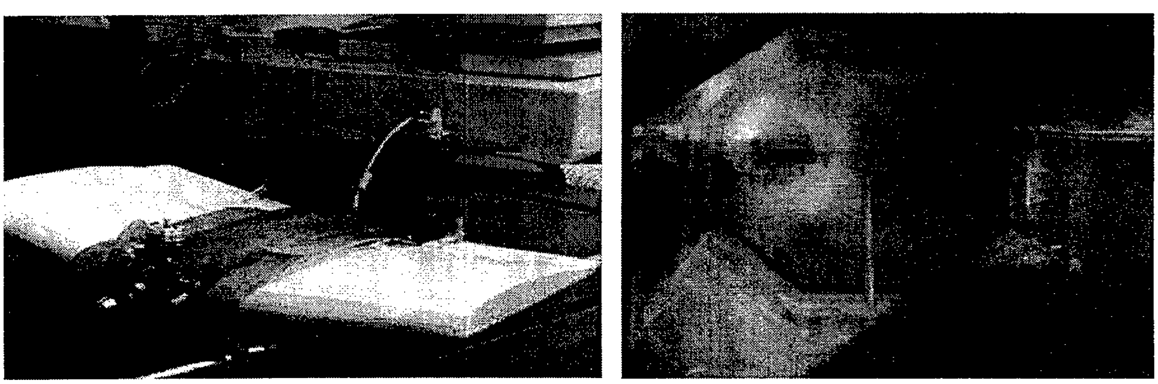

Figure 1. (a) MAVRIC plane developed for University MAV competition.
(b) Upstream view of flow visualization of tip vortex on baseline MAVRIC model

Approach. Our ongoing viscous aerodynamic studies included both experimental and numerical work, both conducted on the ASU main campus. The experimental work was used to validate the computations. In particular, flow visualization and force-balance measurements were performed in the ASU Flow Visualization Tunnel (FVT). The baseline MAV studied was a flying-wing configuration using an Eppler 212 airfoil (Figure 1). The ultimate goal of these force-balance measurements was to determine the effect of different wing-body-juncture and wing-tip designs. Flow-visualization studies showed a significant sensitivity to cant angle, span, and sweep angle of the winglet. Force-balance measurements then gave quantitative results. Ideal aerodynamic designs for MAVs at low Reynolds numbers can now be efficiently optimized through the computations.

Experiments. Low-Reynolds-number experiments were conducted in the ASU Flow-Visualization Wind Tunnel. The experiment specifically examined the effect on lift and drag measurements of adding winglets to the tips of the wing. Flow visualization showed that a low-aspect-ratio wing at low Reynolds numbers features a tip vortex that can extend a distance up to 60% of the chord in the span direction. This large tip vortex is a source of drag and decreased lift. It was also shown that when a winglet is added to the wing, the size of the tip vortex is decreased and moved off of the lifting surface. See Figure 2. A force balance was used for quantitative measurements of lift and drag.

Force-balance measurements were performed in the ASU Flow Visualization Tunnel (FVT) using a six-component force balance. The force balance measurements came from a set of strain gauges that produce a voltage when flexed. The signals are on the order of millivolts for a 1-gram reading. These millivolts are sent to a National Instruments SCXI chassis where they are amplified with a gain of 1000. The amplifier gives a reading with an accuracy of ± 1 gram. The amplifier has 7 channels plus 1 channel for the power supply to the force balance. Three channels were used for lift, drag, and pitching moment. The other channels were used for temperature readings, dynamic pressure readings, and the control of the angle of attack via a stepping motor. The signals were then routed to the computer using a National Instruments Data Acquisition Board.

A graphical LabVIEW program was created to display the lift, drag, pitching moment, temperature, and dynamic pressure. The program was also able to control the angle of attack as well by using a graphical interface. Calibrations were performed and added directly into the LabVIEW program to show data as forces, moments, etc. instead of voltages. A custom sting was designed by an undergraduate and manufactured at the ASU engineering machine shop. The sting was used to attach the model to the force balance and house a pitching mechanism to control the angle of attack of the model.

An aspect-ratio-one wing was used as a reference case. The wing had a 150 mm span and root chord. An Eppler-212 airfoil was used for its high-lift characteristics at low chord Reynolds numbers. Force-balance measurements were taken at various Reynolds numbers between 65×10^3 and 200×10^3. The results showed that the three dimensionality of the experiment largely effects lift and drag.

Results showed that adding winglets makes a noticeable difference in $C_{L\alpha}$, C_{Lmax}, and C_D for a given C_L, but it should be noted that adding winglets increases the overall dimension of the MAV unless the winglet is attached at a 90° cant angle. Winglets with different leading-edge sweep, aspect ratios, and areas were examined to determine the effect of winglet shape and area on performance. This study showed surprisingly that these factors changed the lift and drag characteristics only slightly. Changing the position of the winglet from the leading edge to mid chord and then towards the trailing edge, whether on the upper surface or the lower one, had little effect as well.

A noticeable change in the lift and drag were not seen until the cant angle of the winglet was varied from the 90° position. As the cant angle was decreased toward the horizontal, an expected increase in lift was observed. This is due to the larger projected area of the winglet onto the plane of the wing. However, even more interesting is the fact that adding the winglet, for most positions, added to the drag which is exactly opposite of what was predicted. It is believed that the increased skin-friction drag due to the addition of the winglet is larger than the decrease of induced drag provided by the winglet. The exciting result was that an $O(200\%)$ increase in L/D was observed with the addition of a 30° winglet for $Re_c = 75{,}000$.

Next, a flap was introduced at the trailing edge of the winglet to observe the effect of camber on winglet design. For small flap deflection angles, little or no change was noticed. However, as the flap angle increased it was observed that for a given C_L, C_D increased slightly, but there was no change in $C_{L\alpha}$ or C_{Lmax}. It is believed that if the flap had been slotted instead of bent, then higher C_L values would have been observed.

This experiment has shown that adding a flat-plate winglet to a low-aspect-ratio wing helps to increase $C_{L\alpha}$ and C_L for a given α while decreasing C_D for a given C_L. These results have provided a database for low-Reynolds-number flows that can be used to validate computational models.

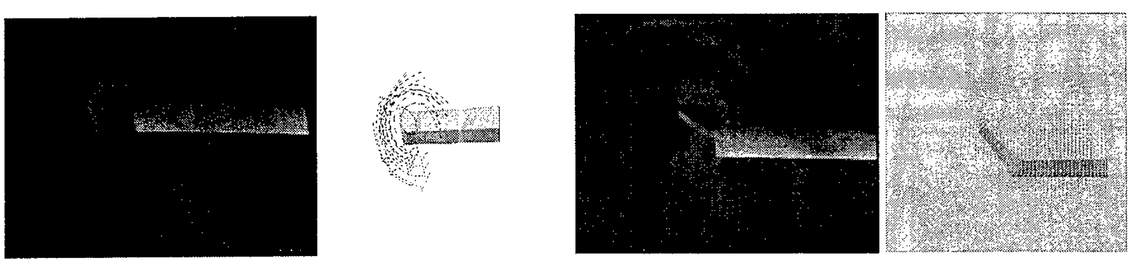

Figure 2. Comparison of experiments and structured-grid computations.

Numerical Simulations. For the design of MAVs, 3-D, unsteady, viscous effects are critical considerations for aerodynamic control. As modern computers become more capable of handling large problems and new faster solution algorithms for these problems are being developed, the only appropriate approach for predicting the flow characteristics is through direct numerical simulations (DNS). In such simulations the full, 3-D incompressible Navier-Stokes (N-S) equations are solved by employing very sophisticated numerical methods that are specially developed for this chord Reynolds

number range, using either finite-difference, finite-element (FEM) or finite-volume methods. DNS avoids the restrictions (e.g. turbulence modeling, weak viscous/inviscid interactions, …) that are inherent in theoretical and other computational models. Because they provide enormous savings in problem size, these simplifications have been widely used by others for parametric studies [eg. Ramamurti 2000]. These restrictions, however, are usually based on high Reynolds numbers and thus may not be completely appropriate for detailed studies of the physics in MAV applications.

In the early stages of the current work, the problem was investigated using structured, single-block grids that were sufficient for solving the 2-D problem accurately and predicting preliminary results for simple 3-D configurations such as a tapered wing. In Figure 2 the comparison between experiment and computation is shown illustrating the dominant tip vortex which affects on the order of 60 % of the span of the MAV at Re = 175,000. Based on this result, the main emphasis of the current work is to minimize the effect of the tip vortex. Blending the wing and fuselage and adding winglets provides a reduction in the extent of these vortices as well as a refocusing of them away from the lifting surface. Adding a winglet to the model moved the vortex away from the airfoil in experiments thus increasing the lift and also reducing the induced drag caused by this vortex. In Figure 2 the velocity vectors at the trailing edge of a wing-winglet model are shown. It was observed that the vortex moved similarly as in experiments. However, the grid-generation scheme chosen was not able to handle these more complicated problems such as wing-winglet or wing-body configurations to a satisfactory accuracy.

The research was then redirected towards unstructured grids and effective solution methods. The FEM was chosen as the computational tool for the in-house code that is used to solve the MAV flowfield. Currently, the mixed velocity-pressure formulation is used together with the P2-P1-elements that satisfy the LBB-stability condition. The motivation for this formulation is that it can be used both for 2-D and 3-D calculations.

Various iterative solution methods have been investigated, including the Conjugate Gradient method, element-by-element solutions, and an explicit node-by-node solution, of which the latter one has shown the most promising behavior although it has not yet been successfully implemented for full-scale problems as of the date of this report.

Meanwhile, other computational tools have been tested. Widely used Cobalt_{60} has been used for both 2-D and 3-D calculations. Although this finite-volume solver is developed mainly for compressible flows, it can be used for incompressible flows as well. The current study has revealed that use of Mach number 0.1 gives good results for incompressible flows. It should also be noted that the use of $M < 0.1$ led to non-physical solutions. Figure 3 shows a comparison between the current 2-D results and experimental results published by Mueller 1999. It should be noted that Mueller also published computational data that agrees with these experimental results.

The 2-D calculations were used both to verify and validate the current approach as well as to study the effects of various parameters and boundary conditions. It was observed that varying the freestream pressure in Cobalt_{60} is the most reliable method to match the

Reynolds number for a given Mach number. Also, use of free-stream boundary conditions instead of fixed inlet velocity led to better solutions.

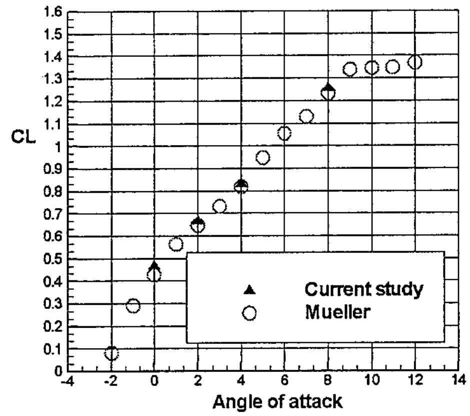

Figure 3. 2-D lift coefficient for Eppler 61.

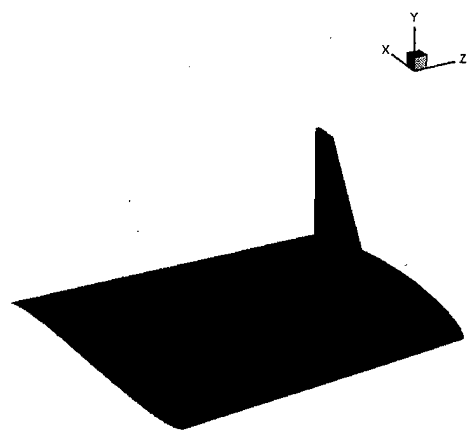

Figure 4. Surface mesh on winglet model

Grid generation for the 3-D case has been done successfully using either GridTool or Gridgen, starting from either an IGES file or a Plot3D file, depending on the current geometry. Figure 4 shows the surface grid on a typical wing-winglet configuration. A structured surface grid is used for most of the model, as it allows one to use a larger subdomain while generating the grid and no database creation is necessary from a Plot3D input file. Use of a structured surface grid also makes post-processing easier. Near the trailing edge, where the wing and winglet are connected, one has to used an unstructured mesh in order to better model the geometry.

The computations using Cobalt_{60} show that the addition of the winglet results in an $O(200\%)$ increase in L/D at zero angle-of attack, which qualitatively agrees with the

experimental results. No quantitative comparison is complete as of yet, as the grid convergence studies are still underway. However, the increase in L/D is apparent in all calculations so far. The dominant tip-vortex affects up to 60% of the half-span of the wing, thus creating negative lift. Addition of a winglet both moves the vortex outward and weakens the strength of it. Velocity vectors 20% chord behind the model are shown in Figure 5 and show clearly the effect of the winglet. Note also that the magnitude of vorticity behind the model is 30% lower when a winglet is added to the model.

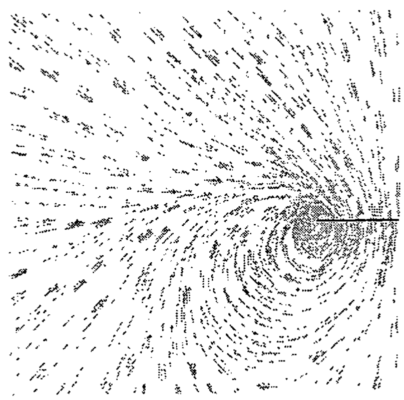

Figure 5a. Velocity vectors behind basic wing configuration at Re= 40,000.

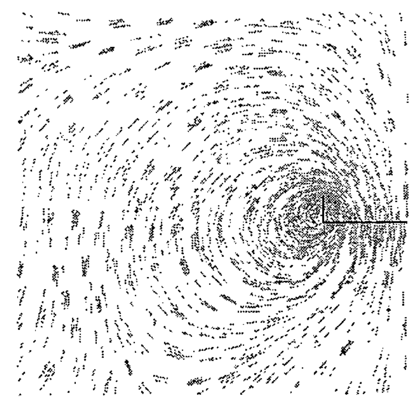

Figure 5b. Velocity vectors behind wing-winglet configuration at Re= 40,000.

As mentioned earlier in this report, we are working toward developing in-house DNS codes and ascertaining the appropriateness of $Cobalt_{60}$ for low-chord-Reynolds-number flows. To this end, adaptive grid refinement that has been successfully developed for our 2-D calculations and is being extended to 3-D. Details of our computational work are provided in Mönttinen et al. (2001).

MAV 2000 Competition.

Over the last decade many issues on university strategy have been the subject of continuous discussion. In particular, industry has submitted inputs about the quality of engineering education and support of university research. Industry now wants engineering schools to direct the education of students to provide hands-on awareness of real-world engineering issues such as product manufacturing, hands-on design, interdisciplinary awareness and teamwork, communication skills (listening, writing, verbal), business skills, and interpersonal relationship skills, while maintaining an emphasis on traditional basic science, mathematics, and engineering fundamentals. University basic research and development can be consistent with and contribute to these goals.

To this end, in our MAV program, undergraduate participation was a key element. Creating an MAV and maintaining any sense of reliability presents incredible challenges in viscous aerodynamics, micro-electronics, micro-propulsion systems, and subsystem multi-functionality. The MAVRIC (Micro Aerial Vehicle Research Initiative and

Competition) team addressed these engineering issues through a student design project and flight competition.

With the support of Lockheed-Sanders, the MAVRIC Team competed for the first time in the Third Annual Micro Aerial Vehicle Competition held at the University of Florida in Spring 1999. Our two entries (a conventional MAV and a blended wing/body design) were both unsuccessful and the team returned with many "lessons learned" and new ideas.

The Fourth Annual MAV Competition was hosted by ASU at the Electronic Proving Grounds (EPG) at Fort Huachuca, Arizona, on May 20, 2000. The competition was sponsored by AFOSR, the Arizona NASA Space Grant Program, the ASU Unsteady Wind Tunnel, EPG, Lockheed-Sanders, and Lockheed-Skunk Works.

The MAV 2000 Competition turned out to be a great success. There were a total of 6 competing teams and 2 displays related to the aerospace field. The teams included ASU, Brigham Young University, Kon Kuk University from Korea, the University of Florida, the University of Notre Dame, and Virginia Polytechnic Institute and State University. The HARVee team from Arizona State University displayed their R/C sized tilt-wing aircraft while a group from NASA Langley Research Center displayed their research on *Dynamics and Control of Biologically Inspired Flight System.*

The teams had the choice of competing in 2 events: (1) The surveillance event required flying the MAV a distance of 630 meters from the launch site and capturing the image of a two-dimensional target. Then the image had to be presented to the judges for verification. The University of Florida was the only team able to fly out and present an image of the target to the judges. The Florida team used a 10-inch aircraft and won the first place prize of $750 for completing this event. (2) The second event was a heavy payload carry. The smallest MAV able to carry a 2-ounce payload for two minutes would win this event. The University of Florida placed first in this event as well using an 11.125-inch MAV. VPI won second place with a 13.25 inch MAV. The prizes for first and second place in this event were $200 and $100, respectively.

Publications and presentations. The following papers were published related to this grant:

Mönttinen, Shortridge, Reed, and Saric: "Adaptive, Unstructured Meshes for Solving the Navier-Stokes Equations for Low-Chord-Reynolds-Number Flows", proceedings of "Fixed, Flapping and Rotary Wing Vehicles at Very Low Reynolds Numbers", edited by Thomas J. Mueller, Notre Dame, June 5-7, 2000, pp. 142-152.

Latek, Reed, and Saric "Implementation of Research Advances into an Operational MAV for the MAV Competition", proceedings of "Fixed, Flapping and Rotary Wing Vehicles at Very Low Reynolds Numbers", edited by Thomas J. Mueller, Notre Dame, June 5-7, 2000, pp. 478-488.

Latek: "Experiments On Low-Reynolds-Number Aerodynamics For Micro Aerial Vehicles", Master's Thesis, Arizona State University, Tempe, Arizona, May 2001.

Mönttinen, Shortridge, Latek, Reed, and Saric: "Adaptive, Unstructured Meshes for Solving the Navier-Stokes Equations for Low-Chord-Reynolds-Number Flows", in "Fixed and Flapping Wing Aerodynamics for Micro Air Vehicle Applications", T.J. Mueller, Editor, AIAA Progress in Astronautics and Aeronautics Series, Volume 195, Pages 61-81, 2001. (Paper originally peer reviewed. Editors decided to create AIAA Progress Series volume from selected accepted papers.)

In addition to the above, the following presentations were given:

Mönttinen, Shortridge, Reed, and Saric: "Adaptive, Unstructured Meshes for Solving the Navier-Stokes Equations", presented in the 16th Arizona Fluid Mechanics Conference, Tempe, Arizona, February 2000.

Latek, Reed, and Saric "Experiments on Low Reynolds Number Aerodynamics for Micro Aerial Vehicles" presented in the 16th Arizona Fluid Mechanics Conference, Tempe, Arizona, February 2000.

Mönttinen, Shortridge, Reed, Saric: "Computational Aspects of Micro Aerial Vehicle Design", APS Division of Fluid Dynamics Conference, Washington, D.C., Nov. 2000.

Latek, Saric, Reed: "Experiments on Micro Aerial Vehicle Aerodynamics", APS Division of Fluid Dynamics Conference, Washington, D.C., November 2000.

Mönttinen, Shortridge, Reed, Saric: "Computational Aspects of Micro Aerial Vehicle Design", 17th Arizona Fluid Mechanics Conference, Tucson, Arizona, February 2001.

Thomas, Mönttinen, Reed: "Unstructured Meshes For Turbine Blade Application", 17th Arizona Fluid Mechanics Conference, Tucson, Arizona, February 2001.

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